COMP/ELEC 524 : Project Final Report

Implementing and Evaluating A MAC Protocol Using Directional Antennas For Mobile Adhoc Networks

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Abstract

In this report we describe the implementation and evaluation of a MAC protocol for mobile ad hoc networks using directional antennas. Use of directional antennas in ad hoc networks can largely reduce the radio interference, thereby improving the packet throughput. Currently ns-2 with Rice/Monarch extensions does not support mobile nodes with directional antennas. We have extended ns-2 to support radio-propagation model of directional antennas in the physical layer. We have also implemented the D-MAC protocol [1], which uses directional antennas, in ns-2. Simulation results show that D-MAC scheme improves performance by allowing simultaneous transmissions that are disallowed when using only omni-directional antennas.

1 Introduction

A wireless, mobile ad hoc network is an autonomous system of mobile nodes, which are typically assumed to be equipped with omni-directional antennas. The medium access control (MAC) protocol performs the challenging tasks of resolving contention amongst nodes while sharing the common wireless channel for transmitting packets. The IEEE 802.11 [3] standard for MAC protocol is based on mobile nodes equipped with omni-directional antennas. However, since the wireless spectrum is scarce, there is a lot of interest in seeking ways to improve bandwidth utilization and throughput. One such method is the use of directional antennas in ad hoc networks which can largely reduce the radio-interference, thereby improving the packet throughput. Using directional antennas may offer several interesting advantages for ad hoc networks, for instance, routing performance can be improved (route discovery or for data delivery). To best utilize directional antennas a suitable MAC protocol must be used.

However, the use of directional antennas for mobile nodes introduces the complex issue of finding the desired direction for transmission or reception using a directional antenna. This issue is particularly critical in an ad hoc network, which has no centralized control,

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and the mobile hosts may have limitations on the size and the complexity/cost of the hardware. Despite these difficulties, the idea of using directional antennas in packet radio has been explored by several researchers in this area. Zander [4] studied the performance improvement that can be achieved by using electronically steer-able adaptive antennas in the slotted ALOHA multi-hop packet radio network.

Recently, many MAC protocols for directional antennas have been proposed. We have studied two such protocols. One of the protocols [1] relies on external information (like GPS) to know the position of other mobile nodes. The other protocol [2] learns the position of other nodes during the operation without relying on external information. We have implemented the MAC protocol described in [1] in *ns-2*, and evaluated its performance on a few network topologies.

The rest of the report is organized as follows: in section 2 we briefly describe the MAC protocol with directional antennas given in [1], in section 3 we outline the implementation details for introducing directional antennas and the MAC protocol in *ns-2*, in section 4 we present the experiments and the results to evaluate the above implementation, finally we summarize our results in the concluding section.

2 Directional MAC (D-MAC) Scheme

The proposed Directional MAC (D-MAC) [1] scheme is similar to IEEE 802.11 in many ways. In 802.11, if a node X is aware of an on-going transmission between some other two nodes (due to receipt of an RTS or CTS from those nodes), node X will not participate in a transfer itself - that is, X will not send a RTS, or send reply to an RTS from another nodes, while the transfer between the other two nodes is in progress. The directional MAC protocols apply a similar logic, but on a per-antenna basis. In brief, if antenna T at node X has received an RTS or CTS related to an on-going transfer between two other nodes, then node X will not transmit anything using antenna T until that other transfer is completed. Antenna T is said to be *blocked* for the duration of that transfer.

Directional MAC (D-MAC) scheme utilizes a directional antenna for sending the RTS packets in a particular direction, whereas CTS packets are transmitted in all directions. In Figure 1, assume that node B has data packet for node C, and also assume that no other data transfers are in progress (so none of the antennas are blocked). In this case, node B sends a *directional RTS (DRTS)* packet including the physical location information of B, in the direction of C. Thus, node A does not receive the DRTS from node B even though node A also exists within B's transmission range. If node C receives the DRTS packet from B successfully, it then returns an *omni-directional CTS (OCTS)* reply. Two location informations are included in the OCTS packet: location of the node sending OCTS (node C) and location of the sender of the corresponding DRTS packet (node B). After the successful exchange of DRTS and OCTS packets, a data packet is sent by node B using a directional antenna. When node C receives the data packet, it immediately sends an ACK to node B using a directional antenna.

Now, during the proposed length of the transmission between B and C, assume that node D, which is a neighbor of node C, has data to transmit to node E. Note that the directional antenna of node D that points towards node C is *blocked*, since node D would have received on this directional antenna the OCTS sent by node C to node B. However, the blocked antenna is different from the directional antenna that points towards node E. Therefore, node D can send a directional RTS packet towards node E. Essentially, if node D knows that its data transmission to node E would not interfere with the other on-going data transfer from B to C, D sends a DRTS control packet to E. As a result, D-MAC scheme can improve performance by allowing simultaneous transmissions that are disallowed when using only omni-directional antennas.

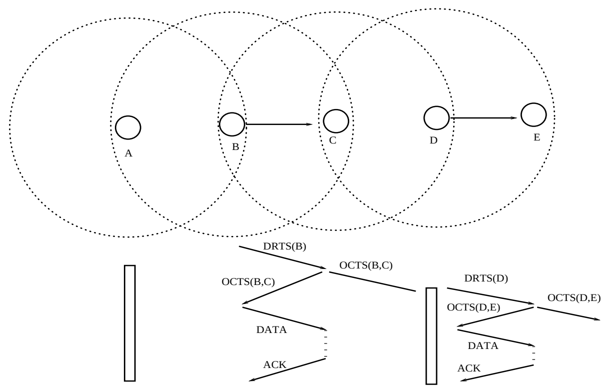

Figure 1: D-MAC Scheme

3 Implementation Details

We have implemented the radio propagation model for directional antennas in *ns-2*. We have also implemented the D-MAC [1] protocol using directional antennas. In the next two subsections, we will describe the changes made to *ns-2* for incorporating radio propagation model and the D-MAC protocol.

3.1 Radio Propagation Model

Currently in *ns-2*, when a node sends a packet, it is broadcast to all nodes in the system. Now, when each of the receiving nodes gets the packet, it calculates the power received depending on its distance from the sender, antenna gains of sender and receiver and other factors. If the received power is above some threshold, it accepts the packet (implying that packet is passed to layers up in network stack) and will do some processing on it, else the packet is discarded. In directional antennas, the radio beam is directed in some particular direction (i.e. the direction of the receiver). Therefore, only few nodes in the same direction should receive the packet sent using directional antennas.

In implementing the radio propagation model, we have kept the semantics of reception of a packet same to the original *ns-2* implementation, i.e. every node in the system will receive the packet. Every node checks for the proper direction and power level before passing it to upper layers of network stack. We have implemented a conical-beam like propagation model for directional antennas. Figure 2 shows the case when the *sender* node uses directional antenna for sending a packet. *Sender* node will send the packet by directing the radio-beam in the direction of receiver, node 7 in the figure.

Now, the energy of the beam will disperse in conical fashion as it traverses the free medium to reach the receiver. So, nodes which lie in this conical beam should receive this packet depending on the distance from the sender. In the implementation, every node will receive the transmitted packet in the physical layer. On reception of a packet, each node checks whether it lies in the direction of the transmitted beam; if not, it discards the packet right-away, otherwise it accepts the packet and sends it to upper layers in the network stack depending on the power level of the received packet which is a function of its distance from the *sender*.

3.2 MAC Protocol for Directional Antennas

We have implemented the MAC protocol for directional antennas as explained in [1]. This protocol assumes the knowledge of exact location of all the nodes in the system. Before

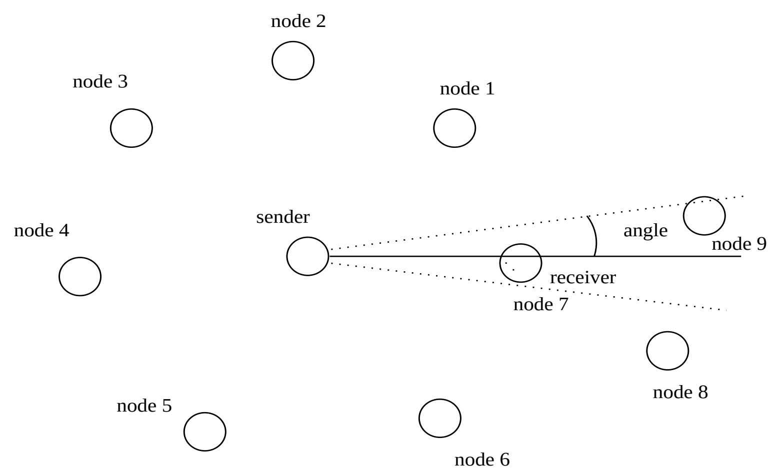

Figure 2: Radio Propagation Model for Directional Antennas

discussing about the changes made in *ns-2*, we will briefly explain how the original *ns-2* implements omni-directional antennas.

3.2.1 Brief overview of MAC IEEE 802.11 implementation in original ns-2

In unmodified *ns-2*, each node has a single omni-directional antenna. This antenna has certain characteristics, like receive gain, transmission gain, etc. And in the implementation, there is a single MAC object attached to every node, referred to as *mac_father* throughout the rest of the report. According to the MAC protocol used, *mac_father* sends (receives) the packets to (from) the physical layer. We will discuss briefly the implementation of the IEEE 802.11 MAC protocol in *ns-2* as this is relevant to our work.

In IEEE 802.11 MAC protocol, a node that intends to send data should first send the RTS packet and on reception of the CTS packet from the intended receiver, should transmit the data (assuming that the data size is higher than the threshold for RTS/CTS exchange). When the *mac_father* attached to a node intends to send the RTS packet, it first starts a defer timer (*mhDefer_)* for *difs* interval. When this timer expires and there is no transmission going on in the channel, it sends the RTS and starts the defer timer (*mhDefer_*) waiting for the CTS; if the channel is busy it starts a backoff timer (*mhBackOff_*). If it receives the CTS before this timer expires, this node will start a defer timer (*mhDefer_*) for *sifs* interval else it would retransmit the RTS. After the expiry of this timer, the *mac_father* can start sending the packet and would start send timer (*mhSend_*), which when expires will cause the retransmission of this data packet (when its ACK does not arrive in time).

3.2.2 Implementation of Directional Antennas

In the original implementation, we observed that the *mac_father* (class Mac802_11) object in a node is the entity which controls all the outgoing and incoming packets to it. It has all the timing information for (re)transmission of packets by means of different timers, like deferring timer, sending timer, receiving timer and backoff timer (*mhDefer_, mhSend_, mhRecv_ and mhBackOff_ respectively*). Since for each directional antenna we need to have separate timers and each of these timers are members of class Mac802_11, we extended this Mac802_11 class to create our directional antenna class, Directional_Antenna. Thus, we are giving interface of multiple antennas at the MAC layer. Additionally, our

Directional_Antenna class has parameters to identify the direction in which this antenna is pointing. Each directional antenna, additionally, has a parameter *father* which points to the *mac_father* object of the same node.

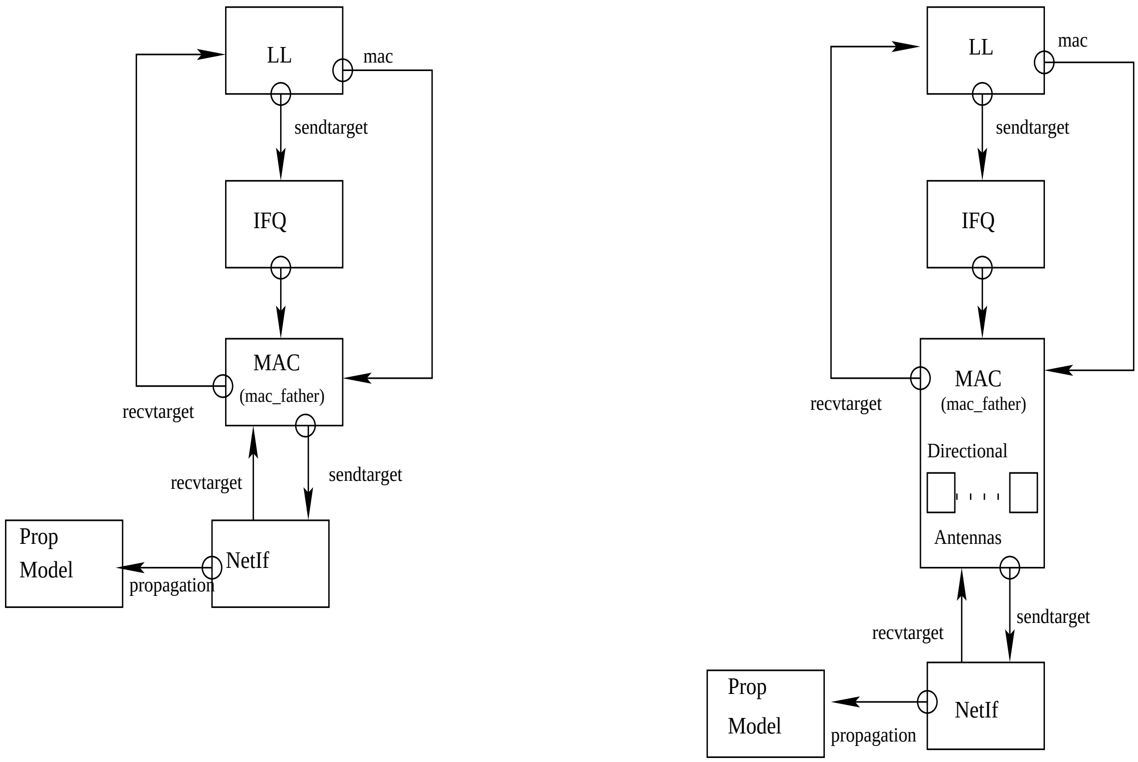

Figure 3: Schematic diagram comparing original mobile node and modified mobile node

Figure 3 compares the architecture of link layer through physical layer of mobile node in original **Rice/Monarch** extension in *ns-2* to that of our modified mobile node which has directional antennas. The *mac_father* object has two members *recvtarget* and *sendtarget* which point to upper and lower layers of the network stack respectively. We have extended the Mac802_11 class to create our directional antennas, so that *recvtarget* and *sendtarget* for these directional antenna objects point to their father's (i.e. Mac802_11's) *recvtarget* and *sendtarget* respectively. So, other layers in network stack do not see the change brought by directional antennas. They see just one MAC object (*mac_father*), to which the other layers in stack (Network Interface layer, Link Layer) pass on the packet as well as receive from.

Figure 4 shows in detail the changes made in the MAC layer of network stack in a mobile node. When the *mac_father* receives packet from layers above it in network stack (i.e. packets for sending), it finds out which directional antenna should it use to send the packet out of the available antennas (if the transmission direction of the packet is known). It would then give this packet to the selected antenna and its work is done. Now, the selected antenna would do the required job of sending the packet, i.e. starting the various timers, contending for the channel, sending the packet in correct direction and retransmitting if the acknowledgment is not received. If the transmission direction of the packet is not known, then *mac_father* would itself transmit this packet.

Also, consider the scenario when the MAC layer receives a packet from lower layer (Network Interface). The *mac_father* would identify the directional antenna which should receive this packet, give this packet to the selected antenna and its job is done. Now, the

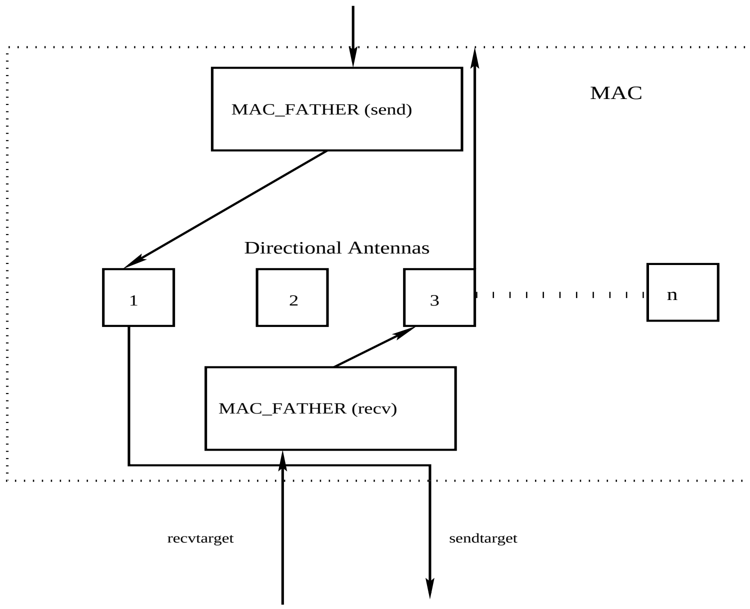

Figure 4: Design of Directional Antennas

selected antenna would do the rest of job as required by the concerned MAC protocol, for example, to check its state (if it receives a CTS, then this antenna should have sent a RTS before, otherwise this CTS is not for this antenna), set various timers (setting NAV if this packet is not for this antenna), etc. If the packet is for this selected antenna, then this antenna would the same processing which was done in original *ns-2* and then pass on to layers (Link Layer in this case) up in network stack.

3.2.3 Implementation of D-MAC Scheme

We modify the existing IEEE 802.11 MAC protocol as follows:

- **RTS/DRTS** - Use *mac_father* to transmit RTS (omni-directional) if the direction of the receiver is not known (as in IEEE 802.11), use directional antenna to transmit DRTS otherwise.
- **OCTS** - Use *mac_father* to transmit OCTS (equivalent to CTS in IEEE 802.11).
- **DATA** - Use directional antenna to transmit DATA packets in the direction of the receiver.
- **ACK** - Use directional antenna to transmit ACK packets in the direction of the node sending data.

4 Performance Evaluation

To evaluate the MAC protocol using directional antennas, we present simulation results on a few network topologies using our modified *ns-2*.

4.1 Simulation Model

We consider a 1500 * 1000 meter rectangular physical space for our simulations. We used *FreeSpace* transmission model. Transmission range of each node is 500 meters and wireless link bandwidth is 2Mbps. Each simulation is performed for a duration of 100 seconds.

4.2 Simulation Results

The performance metric used to evaluate the protocols is the number of data packets being sent and received.

The first scenario considered in our evaluation consists of two stationary nodes 400 m apart, the sender transmitting *cbr* data. We simulate this scenario on the unmodified version and our extended version of *ns-2*. Table 1 gives the number of data packets sent and received in the two simulations. We observe that in both the simulations, the number of data packets remain almost same, which is expected.

Nodes	Using Omni-directional Antenna	Using Directional Antenna
Sender	48455	48438
Receiver	48454	48438

Table 1: Number of *data* Packets sent/received in scenario 1.

The second scenario considered is shown in Figure 5. In this case, A and C are two senders and B and D are the respective receivers. Sender and receivers of both pairs are in range (range is 500 m while they are 400 m apart) of each other. Sender of one pair and sender of another pair are not in range. But, receiver of first pair (i.e. B) is in range of sender of first pair (i.e. C), hence CTS sent by B would be received by C. So, in the IEEE 802.11 MAC protocol, C would defer sending its RTS to D, although B and D are in different directions. But, if we use directional antennas, we expect that C would sent its RTS and can start transmitting the data to D. We simulate this scenario on the unmodified version and our extended version of *ns-2*. Table 2 shows the number of data packets sent and received in this experiment. We observe that number of data packets sent or received for the two sender-receiver pairs is the same when using directional antennas. This shows that two data transmissions don't interfere with each other when using directional antennas. We also observe that when using directional antennas we get almost double the bandwidth than when using omni-directional antennas only. We have attached a screen-shot of *nam* executing this scenario with our modified *ns-2* at the end of this report.

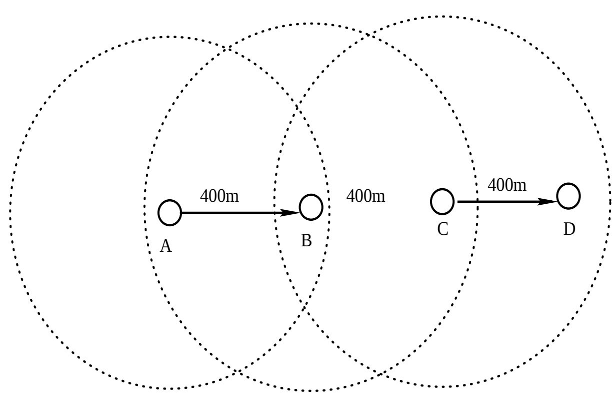

Figure 5: Scenario 2

The third scenario considered is shown in Figure 6. In this case, B and C are two senders and A and D are the corresponding receivers. Sender and receivers of both pairs are in range (range is 500m while they are 400m apart) of each other. But, sender of one pair and receiver of another pair are not in range. Now, the sender of both pairs (B and

Nodes	Using Omni-directional Antenna	Using Directional Antenna
Sender1 (A)	14400	48433
Receiver1 (B)	14399	48428
Sender2 (C)	35180	48432
Receiver2 (D)	35180	48428

Table 2: Number of *data* Packets sent/received in scenario 2.

C) are in range of each other and hence would receive RTS of each other. In IEEE 802.11 MAC protocol, a node upon receiving RTS from another node would set its NAV vector and so would not start its own transmission. But, if we use directional antenna, we expect that both these pairs can start their data transmissions in their intended direction, as their directions are totally opposite. We simulate this scenario on the unmodified version and our extended version of *ns-2*. Table 3 shows the number of data packets sent and received in this experiment. We observe that when using directional antennas we get almost double the bandwidth than when using omni-directional antennas only. This is because the two data transmissions do not interfere with each other.

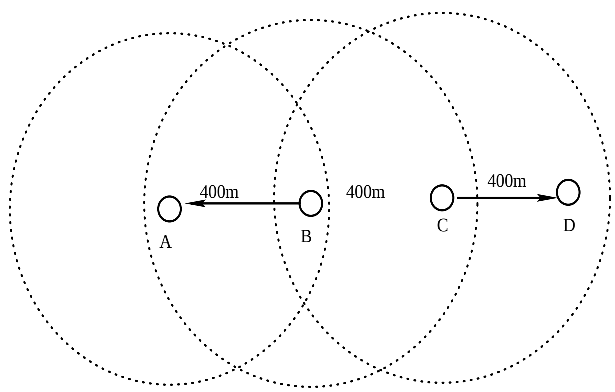

Figure 6: Scenario 3

Nodes	Using Omni-directional Antenna	Using Directional Antenna
Sender1 (B)	24426	48427
Receiver1 (A)	24426	48427
Sender2 (C)	24799	48421
Receiver2 (D)	24799	48421

Table 3: Number of *data* Packets sent/received in scenario 3.

The fourth scenario is shown in Figure 7. In this case we have one *sender* node and one *receiver* node. The *sender-receiver* pair are separated by 400 m and both of them move in the same direction with the same speed of 10 m/sec. We simulate this scenario on the unmodified version and our extended version of *ns-2* to see the effect of mobility on our extended *ns-2* using directional antennas. Table 4 shows the number of data packets sent and received in this experiment. We observe that in both the simulations, the number of data packets remain almost same, which is expected.

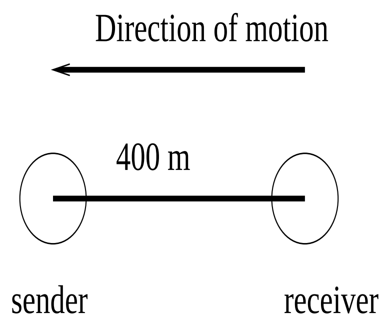

Figure 7: Scenario 4

Nodes	Using Omni-directional Antenna	Using Directional Antenna
Sender	48374	48395
Receiver	48374	48395

Table 4: Number of *data* Packets sent/received in scenario 4.

Conclusion

The current MAC protocols using omni-directional RTS and CTS can waste wireless bandwidth by reserving the wireless medium over a large area. To improve bandwidth efficiency of the previous MAC protocols, various approaches have been proposed. We have implemented and evaluated one such scheme, D-MAC. By simulation studies, we compared D-MAC scheme to the IEEE 802.11 protocol. Our results show that directional MAC protocols can improve performance by allowing simultaneous transmissions that are not allowed in the IEEE 802.11 MAC protocol.

References

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[2] A. Nasipuri, S. Ye, J. You, and R.E. Hiromoto, *A MAC Protocol for Mobile Ad Hoc Networks using Directional Antennas*, IEEE Wireless Communications and Networking Conference (WCNC 2000), Chicago, September 2000.

[3] Brian P. Crow, Indra Widjaja, Jeong Geun Kim, and Prescott T. Sakai, *IEEE 802.11 Wireless Local Area Networks*, IEEE Communications Magazine, 35(9):116p-126p, September 1997.

[4] J. Zander, *Slotted ALOHA Multihop Packet Radio Networks with Directional Antennas*, Electronics Letters, 26(25), 1990.

Link to Our Modified *ns-2*

Machine name - *orval.cs.rice.edu.*
Source code in */usr2/comp524/atuls/ns-allinone-2.1b7a/ns-2.1b7a.*
Tcl scenario files in */usr2/comp524/atuls/ns-allinone-2.1b7a/ns-2.1b7a/scenario.*